

# Preliminary Study into the Magnetically Assisted Blocking of Reverse Current in a Cold Cathode High Current Vacuum Switch

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# **PRELIMINARY STUDY INTO THE MAGNETICALLY ASSISTED BLOCKING OF REVERSE CURRENT IN A COLD CATHODE HIGH CURRENT VACUUM SWITCH\***

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## ***Abstract***

A program of work to investigate the feasibility of using an external magnetic field to cause the blocking of reverse conduction in a vacuum switch will be outlined. The design and build of a suitable device was followed by a program of experimental work during which magnetic fields were applied to the switch in order to attempt to interrupt the current at the first zero crossing of an oscillatory waveform. The design, build and operation of the switch will be described and the results of the experimental work outlined. The results show that an effect, which falls short of complete interruption, could be reproducibly observed and that the magnitude of the effect depended upon the position in time of the applied field relative to the current zero crossing point. A number of observations made during the work have indicated possible methods of improving the reverse blocking performance and these will be outlined in addition to general conclusions.

## **I. Introduction**

EEV Ltd. has recently undertaken the development of a novel generic type of cold cathode vacuum switch, described in detail in [1]. Briefly, the largest of these devices can hold off voltages of up to 24 kV and conduct peak currents up to 550 kA in either unidirectional or oscillatory form with single shot charge transfers of up to 185 coulombs per pulse. Triggering of the switch is achieved using a pulse of 5-10 kV. Novel features of the switch are the use of a nontoxic, easily evaporable cathode and a triggering system consisting of a tubular trigger electrode which additionally acts as a shield to internal insulating surfaces. Sealed devices of up to 10 inches in diameter and 18 inches in length have been manufactured and lifetimes in excess of 5000 shots have now been obtained. During development, it was observed that there was a threshold region where small versions of the device were capable of blocking reverse conduction following an initial half cycle of forward current. At peak currents above this threshold, it was found that the switch conducted reverse current and the question thus arose as to whether the threshold of reverse blocking could be increased by external means such as the application of a magnetic field. Efforts to interrupt pulsed currents in a hot cathode three-electrode gas-filled switch by applying a pulsed magnetic field have been reported before [2]. In this work, the magnetic field confined the discharge to a region of the switch containing an axial metal baffle around which ions and electrons could not diffuse and this resulted in the discharge being extinguished. It would be a considerable advantage if a similar technique could be applied to the new cold cathode switch to ensure that reverse current would not

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build up following the first zero crossing of an oscillatory current. Whilst the hot cathode device was able to interrupt pulsed currents of the order of 100 A, the present aim is to interrupt much larger peak currents at or around the zero crossing point of an otherwise oscillatory current waveform.

## II. Device Design/Initial Tests

The design of the experimental device was based on the smallest of the generic range of cold cathode vacuum switches described in [1]. The envelope was of metal-ceramic construction, with anode, cathode and trigger electrodes. An extra baffle electrode was incorporated between the anode and cathode to provide a site to which the plasma could be guided by the external field. An extra shield electrode was included above the baffle electrode to protect the inner surface of the anode ceramic. Also included were a heated getter and an ion pump to ensure that the internal vacuum was maintained and could be monitored throughout operation. A photograph and cross-sectional diagram of the device are shown in Figures 1 and 2, respectively.

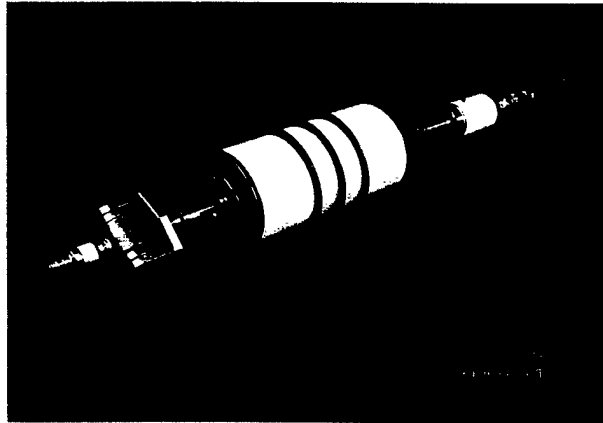


Figure 1. Photograph of experimental device.

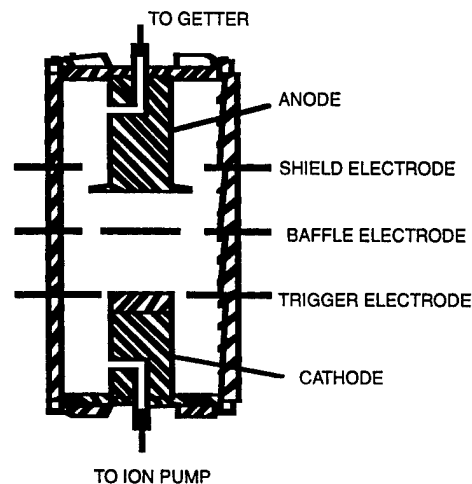
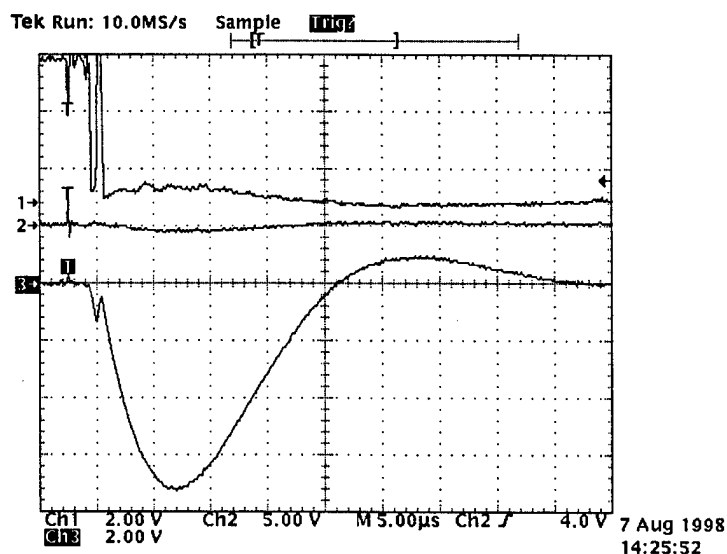


Figure 2. Schematic diagram of experimental device.

The device has an overall length of 35 cm and a diameter of 6 cm. The switch was processed in a manner similar to that for all sealed-off devices, namely pumped under vacuum at high temperature to ensure that impurities which could adversely affect performance were excluded. A number of tests were carried out upon the device following processing and seal off. These were intended to establish the condition of the device and to determine its switching performance prior to investigating the effects of applied magnetic field upon reverse blocking performance. Voltage hold-off was checked with anode positive and all other electrodes connected to cathode at earth potential, and was in excess of 20 kV. The leakage resistance between adjacent pairs of electrodes was measured and in all cases was in excess of 30 G $\Omega$ . Triggering was achieved using a 100 nF capacitor charged to approximately 10 kV. During the preliminary tests the trigger gap was found to break down in the voltage range 8-9 kV. A number of tests were performed in a variety of circuit configurations using discharge capacitors of 16  $\mu$ F and 40  $\mu$ F, producing pulse currents of up to 10 kA and pulse widths of 20 to 30  $\mu$ s. Figures 3 and 4 give typical examples of these initial tests. Anode delay times were observed to be 2-3  $\mu$ s, and current reversals were observed to occur without abrupt changes in the rate of change of current. Figure 3 shows that even in a lightly under-damped circuit, the device exhibits a smooth transition from forward to reverse conduction. These tests demonstrated that the switch complied with general performance expectations, and readily conducted reverse current. The switch was therefore deemed suitable for use in experiments to investigate reverse current blocking with externally applied magnetic fields.



**Figure 3. Current in 16  $\mu$ F circuit at 5 kV charge voltage. Channel 1: Anode voltage at 2 kV/div; Channel 3: Anode current at 2 kA/div.**

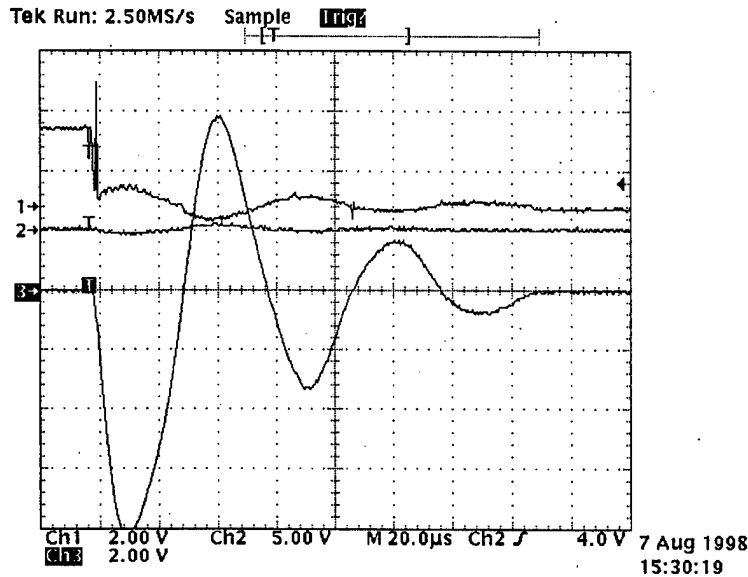
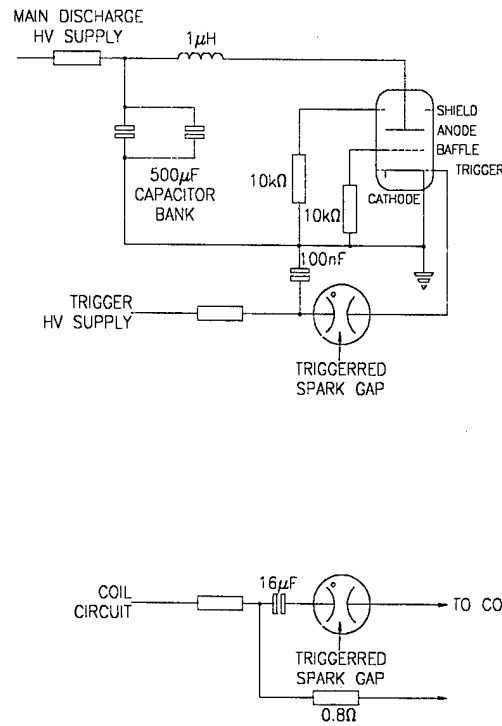


Figure 4. Current in 40  $\mu$ F circuit at 2.5 kV charge voltage. Channel 1: Anode voltage at 2 kV/div; Channel 2: Anode current at 2 kA/div.

### III. Reverse Blocking Experiments

Reverse blocking investigations were performed using a circuit with a 500- $\mu$ F capacitor bank configured to provide a current over-swing of approximately 60% and a half-cycle period of around 150  $\mu$ s. Figure 5 shows the main discharge, trigger and pulsed magnetic field circuits, together with the electrode connections generally used for the switch. Three forms of coil were used to apply radial, axial and circumferential magnetic fields to the switch. The magnetic field could be time-delayed to appear at any desired point on the main anode-cathode current waveform. The operating point for the majority of tests was selected by observing the behaviour of the switch in the test circuit with no external magnetic field applied. At a charge voltage of 1 kV producing a peak current of 8 kA, the switch was observed to interrupt at the first zero crossing point reliably. At charge voltages of 1.0-1.3 kV, corresponding to peak currents of 8.0-10.4 kA, a threshold region where complete and/or partial interruptions occurred was observed. A charge voltage of 1.5 kV, producing a peak current of 12 kA, was thus selected as the operating point because at this level the switch would almost always fail to interrupt or exhibit noticeable current gradient changes as current reversal proceeded. Also, since this operating point was relatively close to the threshold region, the chances were maximised of observing any effect that an externally applied magnetic field might have.



**Figure 5. Top: main discharge circuit and switch trigger circuit; bottom: pulsed circuit for driving the coils.**

### *A. Axial Coil Results*

The axial coil was physically wrapped around the switch itself, and consisted of 50 turns insulated from the device connections by a Mylar sheet. The coil could be positioned in a number of different locations on the envelope of the tube, namely over the baffle/cathode, the trigger/shield and the baffle/anode regions. The circuit shown in Figure 5 was used to apply a pulse to the coil.

At a charge voltage of 7 kV, a pulse current of 3.5 kA is applied to the coil. The results shown in Figure 6 are typical of those generally obtained with the axial coil. The applied magnetic field was observed to cause a transient interruption of duration of about 10  $\mu$ s at the first current zero crossing point, after which reverse current then continued with a change in the observed current slope. The timing of the applied magnetic field in the figure shows maximum coil current at the first current zero. As expected, this turned out to be where the greatest effect was observed. Figure 7 shows a slightly shorter interruption when the pulse applied to the coil was advanced to bring the coil maximum current to a point 50  $\mu$ s before the main current zero crossing. The voltage oscillations observed in the figures on the trigger voltage waveforms, derived from commercially available high voltage probes, are believed to be artifacts of the method of measurement. However, the trigger waveforms demonstrate that even with low applied anode voltages, the anode delay time is still generally below 10  $\mu$ s. There was little or no change in the effects observed as the coil location was moved up and down the switch. Decreasing the coil pulse current to 3.0 kA from 3.5 kA had little or no observed effect on the transient interruption, as can be seen in Figure 8.



### B. Radial and Circumferential Coil Results

The radial coils were also tried in a number of locations on the tube envelope. In general terms, there was no discernible difference between the waveforms observed with and without the applied magnetic field. Very slight "hesitations" in the onset of reverse current were occasionally observed, but these were not consistent and could very occasionally be seen when no external magnetic field was applied. There was no observable effect when the timing of the applied magnetic field was altered. The circumferential coil, which had a relatively large spacing between turns to encourage the magnetic field to fringe and create a circular field pattern in the region of the switch baffle, produced a similar null result to the experiments with the radial coils.

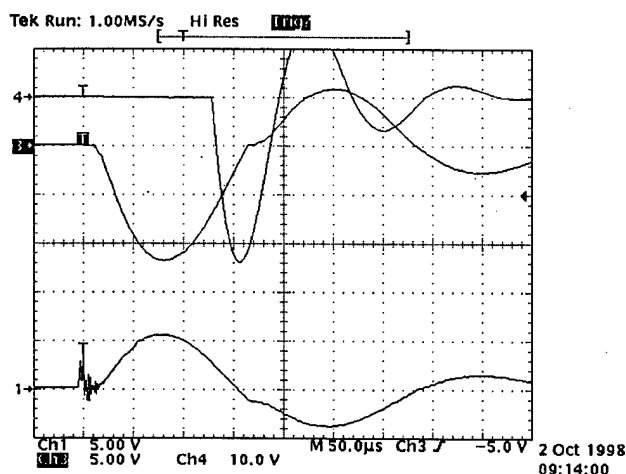


Figure 6. Transient interruption at current zero crossing point. Channel 4: Coil current at 1 kA/div; Channel 3: Switch current at 5 kA/div; Channel 1: Trigger voltage at 5 kV/div.

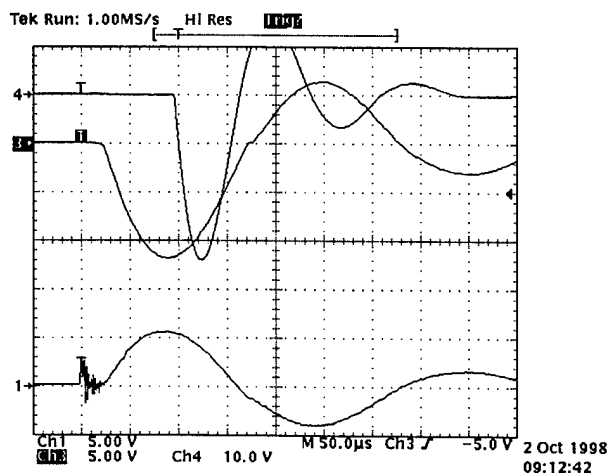


Figure 7. As for Figure 6, but with the maximum peak of coil current timed to occur in advance of the zero crossing point.

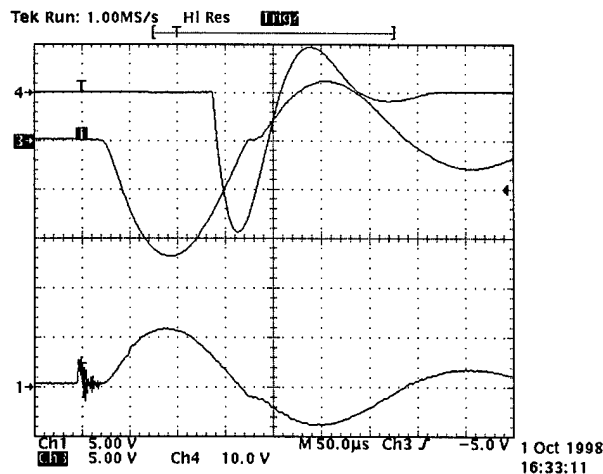


Figure 8. As for Figure 6, but with axial coil current reduced to approximately 3.0 kA.

#### IV. Discussion and Concluding Remarks

Although complete interruption of current at the zero crossing point was generally not observed, an axially applied magnetic field was observed to cause a transient interruption for a period of ten microseconds or so. Generally, the magnitude of the effect was dependant upon the time relation of the magnetic field and the first zero crossing of the main anode-cathode current. If the magnetic field was applied earlier than the first zero crossing then a smaller effect was observed, whilst if the field is applied significantly after the first zero crossing then no effect was observed.

There is some likelihood that the magnitude of the magnetic field actually applied to the internal region around the baffle electrode was not as high as simple calculation might lead one to expect. The peak field produced by the axial solenoid in isolation is of the order of 1 tesla for a peak current of 3 kA. However, the baffle electrode and neighbouring electrodes present a "shorted turn" by transformer action to the applied magnetic field, and thus current would be induced in these electrodes that would tend to annul the effects of the field producing it. Given this, it is particularly encouraging that the applied axial field produced the transient interruptions observed. Overcoming the shorted-turn problem is an area for possible future work, and would involve changing the geometry of the device.

The transient interruptions observed were typically around 10  $\mu$ s in duration. If the inherent de-ionisation time of the plasma could be reduced so that it was shorter than the transient interruption, then there is the prospect that complete interruption could be induced. Again, one way of reducing de-ionisation time is by making geometry changes to reduce the total volume accessible to the conduction plasma, and to provide more metal surface area closer to the conduction plasma for recombination processes to take place.

## V. Acknowledgements

The authors thank Dr. Ian McNab of IAT-UT for his support of this work, and the directors of EEV for permission to publish this work. This work was supported by the U.S. Army Research Laboratory (ARL) under contract DAAA21-93-C-0101.

The views expressed herein are those of the authors and do not necessarily reflect those of GEC, plc.

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